Emerging Energy-Efficient Technologies for Industry

Ernst Worrell, Nathan Martin, Lynn Price, Michael Ruth, Lawrence Berkeley National Lab.
Neal Elliott, Anna Shipley, Jennifer Thorn, American Council for an Energy Efficient Economy

ABSTRACT

U.S. industry consumes approximately 37% of the nation's energy to produce 24% of the nation's GDP. Increasingly, society is confronted with the challenge of moving toward a cleaner, more sustainable path of production and consumption, while increasing global competitiveness. Technology is essential in achieving these challenges. We report on a recent analysis of emerging energy-efficient technologies for industry, focusing on over 50 selected technologies. The technologies are characterized with respect to energy efficiency, economics and environmental performance. This paper provides an overview of the results, demonstrating that we are not running out of technologies to improve energy efficiency, economic and environmental performance, and neither will we in the future. The study shows that many of the technologies have important non-energy benefits, ranging from reduced environmental impact to improved productivity, and reduced capital costs compared to current technologies.

INTRODUCTION

In 1998 the American Council for an Energy Efficient Economy (ACEEE), Davis Energy Group and E-source published "Emerging Energy-saving Technologies and Practices for the Buildings Sector," which provided data on technologies with the largest potential savings, including likely costs, savings and date of commercialization (Nadel et al., 1998). As that report and others like it demonstrate, the assessment of emerging technologies can be useful for identifying R&D projects, identifying potential technologies for market transformation activities, providing common information on technologies to a broad audience of policy-makers, and offering new insights into technology development and energy efficiency potentials.

Recently, there has been increasing interest in improving the assessment of emerging technologies with respect to the U.S. industrial sector. With the support of Pacific Gas and Electric Co. (PG&E Co.)[1], New York State Energy Research & Development Authority, U.S. Department of Energy, U.S. Environmental Protection Agency, Northwest Energy Efficiency Alliance, and the Iowa Energy Center, staff from Lawrence Berkeley National Laboratory and ACEEE produced the report described in this paper (Martin et al., 2000). The goal of the report was to collect information on a broad array of potentially significant emerging energy-efficient industrial technologies and carefully characterize a sub-group of roughly 50 key technologies.

---

[1] The PG&E Co. program is funded by California utility customers and is administered by Pacific Gas and Electric Company under the auspices of the California Public Utilities Commission.

In the report our use of the term "emerging" denotes technologies which are both pre-commercial but near commercialization and technologies which have already entered the market but have less than 5% of current market share. We also have chosen technologies which are energy-efficient (i.e. use less energy than existing technologies and practices to produce the same product), and may have additional so-called non-energy benefits.

INDUSTRIAL ENERGY USE IN THE UNITED STATES

Industrial activities are still a key component of U.S. economic output. In 1997, industrial activities accounted for 24% of U.S. gross domestic product—U.S. GDP that year was $8,300 billion—and employed 27 million full and part-time employees (BEA, 2000). Within the industrial sector, manufacturing activity, which consists of all industrial activity outside of agriculture, mining, and construction, accounts for 70% of industrial value added (BEA, 2000). In 1998, the United States consumed 94 Quadrillion Btu (99 EJ)[2] of primary energy or 25% of world primary energy use (U.S. EIA, 2000). Within the various sectors of the U.S., the industrial sector remains a significant energy user, consuming nearly 40% of primary energy resources (Table 1). The industrial sector is extremely diverse and includes agriculture, mining, construction, energy-intensive industries, and non-energy intensive manufacturing.

Table 1 Historical Share of Industrial Primary Energy Use in the United States

	Units	**1950**	**1970**	**1990**	**1998**
Total U.S.	Quads (EJ)[*]	34.6 (36.5)	67.9 (71.6)	84.1 (88.7)	94.2 (99.4)
Total Industry	Quads (EJ)	16.2 (17.1)	29.6 (31.3)	32.1 (33.9)	35.4 (37.4)
Percent share	%	47%	44%	38%	38%

Source: US EIA, 2000

Energy is necessary to help our industries create products; however, we are increasingly confronted with the challenge of moving society toward a cleaner, more sustainable path of production and consumption. The development of cleaner, more energy-efficient technologies can play a significant role in limiting the environmental impacts associated with many industries while enhancing productivity and reducing manufacturing costs. The demand for energy to produce manufactured products is related to the volume of production as well as the efficiency of the equipment used in the manufacturing processes. A broad proxy for efficiency is its inverse, energy intensity, or the amount of energy required to produce a unit of output. Research about the U.S. has shown that since the first oil price shock in 1973 manufacturing energy consumption would have been significantly higher were it not for decreases in energy intensity.[3] As long as they can remain competitive, businesses often will choose to operate existing equipment and technology throughout its useful lifetime, which can run for 20 years or more for large pieces of equipment such as cement kilns or blast

---

[2] In the report we present energy consumption and energy intensity information in both British thermal units (Btus) and standard international units (joules), as the latter is the unit of international communication on energy issues. When appropriate we do note conversion factors. One quadrillion Btu (10^18) equals 0.95 exajoules (EJ) and one metric tonne equals 0.907 short tons.

[3] Golove and Schipper (1996) whose long term analysis of the U.S. manufacturing sector from 1958 to 1991 found that "declines in energy intensity played the dominant role in limiting actual energy consumption," while Belzer et al. (1995) found that energy intensity declines accounted for over half of the energy savings in the industrial sector.

furnaces. At some point, however, businesses are faced with investment in new capital stock. At this decision point, new and emerging technologies compete for capital investment alongside more established or mature technologies. Even if a standard technology is chosen, it is likely to be more efficient than the equipment it is replacing. Understanding the dynamics of what drives these decisions to invest in the new and efficient technologies is important to better understand the drivers of technology change and their effect on industrial energy use. Barriers for technology transfer in the industrial sector include corporate decision-making rules, lack of information, limited capital availability, shortage of trained personnel (especially in small and medium sized enterprises), low energy prices, and the "invisibility" of energy savings.

Many new technologies follow a traditional "S" curve adoption path whereby a small segment of the industry known as early adopters, embraces a new and unproven technology despite high costs and potential risks. As the technology becomes more common, the perceived risks decrease and the cost of the technology declines. The period needed to achieve a significant market share may vary and depends on the technology characteristics, as well as characteristics of the market and the particular sector. Among the factors that tend to increase rates of market penetration, but that are not typically captured in standard models, are transmissions of more complete information about technology attributes, a growing consumer and business familiarity with the technologies, and the awareness of environmental impacts associated with the technologies. Figure 1 shows a typical "S" curve of the adoption of continuous casting technology in the U.S. iron and steel industry. Although the technology eventually reached saturation, it took much longer in the U.S. than in other steel producing countries[4].

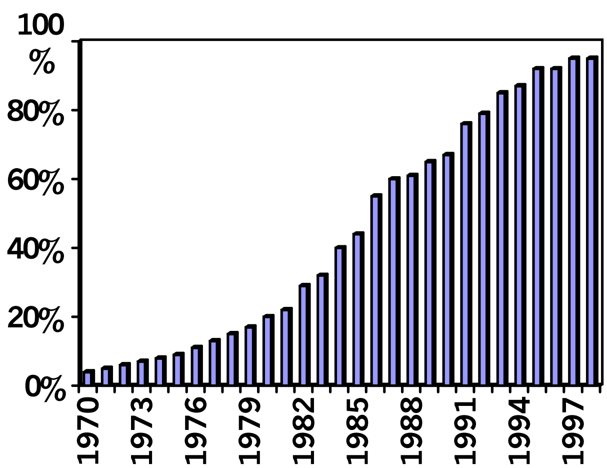

Figure 1. Continuous Casting Use in the United States Iron and Steel Industry, as Share of Steel Production (1970-1998). Source: IISI, 2000

Many innovation and energy polices focus on accelerating the rate of adoption of specific technologies, by reducing the costs or perceived risks of the technology. Various programs try to lower the barriers simultaneously in some steps. A wide array of policies, to

[4] In Italy, and South Korea, and Japan for example 96% or more of steel was continuously cast by 1993, whereas only 85% was continuously cast in the U.S. at that time.

increase the implementation rate of new technologies, has been used and tested in the industrial sector in industrialized countries with varying success rates. We will not discuss general programs and policies in this report but refer to the literature (see e.g. Worrell et al., 1997, Alliance et al., 1997, Bernow et al., 1999, and Martin et al., 1999). With respect to technology diffusion policies there is no single instrument to reduce the size of the barriers; instead, an integrated policy accounting for the characteristics of technologies, stakeholders and countries addressed is needed.

TECHNOLOGY SELECTION AND DESCRIPTION

The project started with the identification of approximately 200 emerging industrial technologies through a review of the literature, international R&D programs, databases and studies. The review was not limited to U.S. experiences, but rather tried to produce an inventory of international technology developments. For an overview of the total list of technologies see Martin et al. (2000). Based on the literature review and the application of initial screening criteria, we identified and developed profiles for 54 technologies. The technologies themselves range from highly specific technologies that can be applied in a single industry to the more broadly cross-cutting technologies, which can be used in many industrial sectors.

Each of the selected technologies has been assessed with respect to energy efficiency characteristics, likely energy savings by 2015, economics, environmental performance, as well as needs to further the development or implementation of the technology. The technology characterization includes a two-page description and a one-page table summarizing the results for the technology. Table 2 provides an example of the summary table for near net shape casting for the iron and steel industry. This technology combines casting and hot rolling, saving energy and increasing productivity. Several steel plants in the U.S. already use thin slab casting, the current commercial status of near net shape casting.

SUMMARY OF RESULTS

Table 3 provides an overview of the 54 characterized emerging technologies. We have evaluated energy savings in two different ways. The first column of Table 3 (Total Energy Savings) shows the amount of total manufacturing energy that the technology is likely to save in 2015 in a business-as-usual scenario. The second column (Sector Savings) reflects the savings relative to expected energy use in the particular sector. We believe that both metrics are useful in evaluating the relative savings potential of various technologies.

Economic evaluation of the technology is identified in the summary table by simple payback period, defined as the initial investment costs divided by the value of energy savings less any changes in operations and maintenance costs. We chose this measure since it is frequently used as a shorthand evaluation metric among industrial energy managers. As the table notes, payback times for the technologies range from the immediate to 20 years or more. Of the 54 technologies profiled, 31 have estimated paybacks of 3 years or less.

Table 2. Example of Summary Table for Near Net Shape Casting in the Steel Industry.

Near net shape casting/strip casting				
steel-2				
Replace current continuous casting with direct near net shape casting				
Market Information:				
Industries		Iron and Steel		SIC 331
End-use(s)		Process heating		
Energy types		Gas, electricity		
Market segment		New		Greenfields & refit of existing facilities. Some retrofit applications
2015 basecase use	Mtons	115.6		AEO 2000, continuous casting output
Reference technology				
Description	Continuous casting/hot rolling			
Throughput or annual op. hrs.	tons	1		Unit consumption presented. Casters range from 150 to 3,000 kton/y
Electricity use	kWh	206		Worrell et al., 1999
Fuel use	MBtu	2.8		Worrell et al., 1999
Primary energy use	MBtu	4.6		Worrell et al., 1999
New Measure Information:				
Description	Near net shape casting/thin strip casting			
Electricity use	kWh	30		Worrell et al., 1997, DeBeer, 1999
Fuel use	MBtu	0.3		Worrell et al., 1997. DeBeer, 1999 estimates 0.0
Primary Energy use	MBtu	0.6		
Current status		Commercialized		Near net beams but not yet flat rolled products
Date of commercialization		1995		No flat rolled caster yet commercial
Est. avg. measure life	Years	20		Worrell et al., 1999
Savings Information:				
Electricity savings	kWh/%	176	90%	
Fuel savings	MBtu/%	2.5	90%	
Primary energy savings	MBtu/%	4.0	90%	
Penetration rate		high		
Feasible applications	%	30%		Apply to non high end steel products, Worrell et al.,1999
Other key assumptions				
Elec svgs potential in 2015	GWh	6093		Savings applied to feasible applications for 2015 output
Fuel svgs potential in 2015	Tbtu	86		Savings applied to feasible applications for 2015 output
Primary energy svgs potential in 2015	Tbtu	137.6		6% savings. Primary energy consumption of 2144 TBtu in 2015
Cost Effectiveness				
Investment cost	$	31		Assume 15% less than conventional casting systems. Full retrofit cost $103
Type of cost		incremental		
Change in other costs	$	-40		Worrell et al. 1997
Cost of saved energy (elec)	$/kWh	-0.20		
Cost of saved energy (fuel)	$/Mbtu	-14.19		
Cost of saved energy (primary)	$/Mbtu	-8.85		
Simple payback period	Years	0.6		Based on $2/Mbtu average 1994 primary energy for steel
Internal rate of return	%	157%		
Key non energy factors				
Productivity benefits		significant		reduced capital costs, reduced production time
Product quality beneifts		somewhat		improved surface properties
Environmental benefits		somewhat		reduced emissions
Other benefits				
Current promotional activity	H,M,L	high		conferences, marketing by suppliers, research consortiums
Evaluation				
Major market barriers		technical challenges		Also, CSP flat rolling plants limited
Likelihood of success	H,M,L	high		
Recommended next steps		R&D		
Data quality assessment	E,G,F,P	Good		Significant literature; limited field data
Sources:				
2015 basecase				EIA, 1999
Basecase energy use				Worrell et al. 1999
New measure energy savings				Worrell et al., 1997
Lifetime				Worrell et al. 1999
Feasible applications				SMS, 1995; Tomasseti, 1995, Kuster, 1996
Costs				DeBeer, 1999
Key non energy factors				SMS, 1995; Tomasseti, 1995, Kuster, 1996, Worrell et al. 1999

Table 3. Summary of Profiled Emerging Industrial Technologies

Technology	Sector	Total Energy Savings[1]	Sector savings[2]	Simple Payback	Environ. Benefits	Other Benefits[3]	Suggested Next Steps
Advanced forming	Aluminum	medium	low	Immed.		P	R&D
Efficient cell retrofit designs	Aluminum	high	high	2.7	somewhat		dissemination
Improved recycling technologies	aluminum	medium	low	4.5	significant	P	demonstration
inert anodes/wetted cathodes	aluminum	high	high	4.0	significant	P	R&D
Roller kiln	ceramics	medium	high	1.9	significant	P	demonstration
Clean fractionation - celluose pulp	chemicals	low	low	1.9	significant	P	demonstration
Gas membrane technologies-chemicals	chemicals	low	low	10.2	significant	P	dissemination
Heat recovery technologies – chem.	chemicals	medium	low	2.4		P	dissem., demo
Levulinic acid from biomass (biofine)	chemicals	low	low	1.5	significant	P	demonstration
Liquid mebrane technologies – chem.	chemicals	low	low	11.2	significant		dissemination
New catalysts	chemicals	low	low	7.9	somewhat	P	R&D
Autothermal reforming-Ammonia	chemicals	high	low	3.7	significant	P	dissemination
Plastics recovery	plastics	medium	low	2.8	compelling		demonstration
Continuous melt silicon crystal growth	electronics	medium	high	Immed.	somewhat	Q, P	R&D
Electron Beam Sterilization	food processing	high	high	19.2		P, Q	R&D
Heat recovery - low temperature	food processing	medium	low	4.8			dissemination
Membrane technology - food	food processing	high	high	2.2	somewhat	P, Q	dissem., R&D
Cooling and storage	food processing	medium	low	2.6	somewhat	P, Q	dissem., demo
100% recycled glass cullet	glass	medium	high	2.0	significant		demonstration
Black liquor gasification	pulp and paper	high	high	1.5	somewhat	S	demonstration
Condebelt drying	pulp and paper	high	low	65.2		P	demonstration
Direct electrolytic causticizing	pulp and paper	low	low	n.a.	somewhat		R&D
Dry sheet forming	pulp and paper	medium	low	48.3	somewhat		R&D, demo
Heat recovery – paper	pulp and paper	high	low	3.9	somewhat		demonstration
High Consistency forming	pulp and paper	high	high	Immed.	somewhat		demonstration
Impulse drying	pulp and paper	high	low	20.3		P	demonstration
Biodesulfurization	pet. refining	low	low	1.8			R&D, demo
Fouling minimization	pet. refining	high	high	Immed.		P	R&D
BOF gas and sensible heat recovery	iron and steel	medium	low	14.7	significant		dissemination
Near net shape casting/strip casting	iron and steel	high	high	Immed.	somewhat	P,Q	R&D
New EAF furnace processes	iron and steel	high	high	0.3	somewhat	P	field test
Oxy-fuel combustion in reheat furnace	iron and steel	high	low	1.2	significant		field test
Smelting reduction processes	iron and steel	high	high	Immed.	significant		demonstration
Ultrasonic dying	textile	medium	low	0.3	compelling	P, Q	demonstration
Variable wall mining machine	mining	low	low	10.6		P,S	demonstration
Hi-tech facilities HVAC	cross-cutting	medium	high	4.0		P, Q	disseminaiton
Advanced lighting technologies	cross-cutting	high	high	3.0		Q, P, S	dissem., demo
Advanced lighting design	cross-cutting	high	high	1.3		P, Q, S	dissem., demo
Advance ASD designs	cross-cutting	high	low	1.1		P	R&D
Advanced compressor controls	cross-cutting	medium	low	0.0		Q, P	dissemination
Compressed air system management	cross-cutting	high	high	0.4		Q, P	disseminaiton.
Motor diagnostics	cross-cutting	low	low	Immed.		P	dissem., demo
Motor system optimization	cross-cutting	high	high	0.8	somewhat	P, Q	dissem., training
Pump efficiency improvement	cross-cutting	high	high	3.0		P	dissem., training
Switched reluctance motor	cross-cutting	medium	low	7.4		P	R&D
Advanced lubricants	cross-cutting	medium	low	0.1	significant	P	dissemination.
Anearobic waste water treatment	cross-cutting	medium	low	0.8	significant	P	dissem., demo
High efficiency/low Nox burners	cross-cutting	high	low	3.1	significant	P,Q	dissem., demo
Membrane technology wastewater	cross-cutting	high	low	4.7	significant	P	dissem., R&D
Process Integration (pinch analysis)	cross-cutting	high	low	2.3	somewhat	P	dissemination
Sensors and controls	cross-cutting	high	low	2.0	somewhat	P,Q	R&D, demo, dissem.
Advanced CHP turbine systems	cross-cutting	high	high	6.9	significant		policies
Advanced reciprocating engines	cross-cutting	high	high	8.3		P, Q	R&D, demo
Fuel cells	cross-cutting	high	high	58.6	Significant	P, Q	demonstration
Microturbines	cross-cutting	high	low	n.a.		P, Q	R&D, demo

Notes: 1. "High" could save more than 0.1% of manufacturing energy use by 2015, "medium" saves 0.01 to 0.1%, and "low" saves less than 0.01%.
2. "High" could save more than 1% of sector energy use by 2015, "medium" saves 0.1 to 1%, and "low" saves less than 0.1%.
3. P=productivity, Q=quality, S=safety.

Energy savings are most often not the determining factor in the decision to develop or to invest in an emerging technology. Over two-thirds of technologies not only save energy but yield environmental or other benefits, so-called non-energy benefits. The non-energy benefits are pre-dominantly increases in productivity through reduced capital costs or increased throughput compared to state-of-the-art technology. Technologies are not simply developed and then seamlessly enter existing markets. The acceptance of emerging technologies is often a slow process that entails active research and development, prototype development, market demonstration, and other activities. In Table 3 we summarize the recommendations for the primary activities that can be undertaken to increase the rate of uptake of these technologies.

Table 4 presents the technologies rated according to their primary energy savings (i.e., accounting for losses in the production and delivery of electricity). These savings values represent the estimated 2015 implemented savings under a business-as-usual scenario (i.e. excluding policy efforts to stimulate adoption of a specific technology). As expected, the cross-cutting technologies (motor systems, lighting, utilities) save the largest amount of primary energy, followed by selected specific technologies in the energy-intensive sectors (steel, petroleum, paper, aluminum, and chemicals). However, this does not mean that sector-specific technologies should be overlooked, as many of these may save substantial amounts of energy, or have important additional benefits.

Table 4. Projected 2015 Implemented Primary Energy Savings Potential

Technology	Code	Sector	Savings (TBtu)
Motor system optimization	Motorsys-5	cross-cutting	1502
Pump efficiency improvement	Motorsys-6	cross-cutting	1004
Advanced reciprocating engines	Utilities-2	cross-cutting	777
Compressed air system management	Motorsys-3	cross-cutting	563
Advanced lighting technologies	Lighting-1	cross-cutting	494
Advanced CHP turbine systems	Utilities-1	cross-cutting	484
Advanced lighting design	Lighting-2	cross-cutting	231
Fuel cells	Utilities-3	cross-cutting	185
Near net shape casting/strip casting	Steel-2	iron and steel	138
Sensors and controls	Other-5	cross-cutting	137
Fouling minimization	Refin-2	pet. refining	123
Membrane technology wastewater	Other-3	cross-cutting	118
Microturbines	Utilities-4	cross-cutting	67
Electron Beam Sterilization	Food-1	food processing	64
Black liquor gasification	Paper-1	pulp and paper	64
Efficient cell retrofit designs	Alum-2	aluminum	46
Process Integration (pinch analysis)	Other-4	cross-cutting	38
Autothermal reforming-Ammonia	Chem-7	chemicals	37
High Consistency forming	Paper-6	pulp and paper	37
Condebelt drying	Paper-2	pulp and paper	34

Non-Energy Benefits

While energy and environmental concerns factor into technology investment decisions at many industrial facilities, it is frequently the productivity and product quality benefits that most frequently ensure the adoption of a technology. Improvements in productivity and quality contribute significantly to the economic attractiveness of a given technology and may indeed be the largest deciding factor in technology investments. Thirty-five technologies in this study had “significant” or “compelling” productivity, quality, or other non-energy benefits (see Table 5).

Table 5. Non-Energy benefits of Emerging Energy-Efficient Technologies.

Technology	Code	Productivity Benefits	Product Quality Benefits	Other Non-energy Benefits	
Ultrasonic dying	Textile-1	Compelling	Compelling	None	
Advanced forming	Alum-1	Compelling	None	None	
Direct electrolytic causticizing	Paper-3	Compelling	Somewhat	None	
Motor diagnostics	Motorsys-4	Compelling	Somewhat	Somewhat	May be able to avoid plant capital expansions due to increased production
Liquid membrane technologies-chemicals	Chem-5	None	None	Significant	Investment 10% less than conventional installation
Biodesulfurization	Refin-1	None	Significant	None	
Dry sheet forming	Paper-4	None	Significant	None	
Gas membrane technologies—chemicals	Chem-2	None	Somewhat	Significant	Investment 10% less below conventional installation
Oxy-fuel combustion in reheat furnace	Steel-4	Significant	None	None	
New EAF furnace processes	Steel-3	Significant	None	None	
Efficient cell retrofit designs	Alum-2	Significant	None	None	
Fouling minimization	Refin-2	Significant	None	None	
Levulinic acid from biomass (biofine)	Chem-4	Significant	None	Significant	Makes the production of levulinic acid economical
Advanced CHP turbine systems	Utilities-1	Significant	Significant	None	
High Consistency forming	Paper-6	Significant	Significant	None	
Sensors and controls	Other-5	Significant	Significant	None	
Electron beam sterilization	Food-1	Significant	Significant	None	
Motor system optimization	Motorsys-5	Significant	Significant	Significant	Reduced fan speed can reduce worker noise exposure
Advanced reciprocating engines	Utilities-2	Significant	Significant	Somewhat	Can allow expansions without needing to upgrade utility service, and can allow for peak load shaving
Microturbines	Utilities-4	Significant	Significant	Somewhat	Can allow expansions without needing to upgrade utility service, and can allow for peak load shaving
Pump efficiency improvement	Motorsys-6	Significant	Significant	Somewhat	Ability to downsize equipment and free up space
Near net shape casting/strip casting	Steel-2	Significant	Somewhat	None	
Continuous melt silicon crystal growth	Electron-1	Significant	Somewhat	None	
Impulse drying	Paper-7	Significant	Somewhat	None	
Condebelt drying	Paper-2	Significant	Somewhat	None	
Advance ASD designs	Motorsys-1	Significant	Somewhat	None	
Advanced lubricants	Motorsys-8	Significant	Somewhat	None	
Advanced compressor controls	Motorsys-2	Significant	Somewhat	Significant	May avoid need for addition compressor purchase or allow retirement of existing compressor with resulting reduced O&M and salvage value
Compressed air system management	Motorsys-3	Significant	Somewhat	Significant	May avoid need for addition compressor purchase or allow retirement of existing compressor with resulting reduced O&M and salvage value
Inert anodes/wetted cathodes	Alum-4	Significant	Somewhat	Somewhat	Safety
Clean fractionation—cellulose pulp	Chem-1	Somewhat	None	Significant	Lower production costs
Variable wall mining machine	Mining-1	Somewhat	None	Significant	Improved working conditions and safety
Switched reluctance motor	Motorsys-7	Somewhat	Significant	None	
Advanced lighting technologies	Lighting-1	Somewhat	Somewhat	Significant	Added energy savings with use of controls and sensors; faster start-up
Advanced lighting design	Lighting-2	Somewhat	Somewhat	Significant	Added energy savings w/ task lighting; reduced HVAC load; faster start-up

Environmental Benefits

For some industries, the costs of complying with environmental regulation can be an important driver for decisions to invest in particular technologies, especially in the nonattainment areas. Of the 54 technologies profiled, 20 had environmental benefits that were either compelling or significant, e.g. reduction criteria pollutant emissions. The benefits mainly fall in the area of reduction of wastes and emissions of criteria air-pollutants. The use of environmentally friendly emerging technologies is often most compelling when it enables the expansion of incremental production capacity while not requiring additional environmental permitting. In selected cases, the use of environmental selection-criteria to invest in these technologies is part of a larger, long-term business strategy towards sustainable development and to stay ahead of the regulatory curve.

SUGGESTED ACTIONS

From a national energy policy perspective, it is important to understand which technologies have both a high likelihood of success and high energy savings. While various audiences may be interested in sector-specific or regional-specific technologies, the technologies listed in Table 6 are intended to provide guidance to those interested in the impact of energy-saving technologies on a more national level. This table also identifies the recommended next steps appropriate for each technology.

Each technology is at a different point in the development or commercialization process. Some technologies still need further R&D to address cost or performance issues. Other technologies are ready for demonstration. Some technologies have already proven themselves in the field, and the market needs to be informed on the benefits and market channels needed to develop skills to deliver the technology. Table 3 outlined the recommendations to support future development of the technologies. We note that this is not an endorsement of any particular technology. This is an issue that will ultimately be decided by the technology purchasers and users. However, the actions are intended to help identify whether a technology is both technically and economically viable and whether it is robust enough to accommodate the stringent product quality demands in various manufacturing establishments.

Seventeen emerging technologies could benefit from additional R&D. We suggest further R&D for several primary metal technologies (e.g. advanced forming, inert anodes/wetted cathodes in aluminum and near net shape casting in steel), several cross-cutting motor and utility technologies (e.g. advanced ASD designs, switched reluctance motor, advanced reciprocating engines, micro-turbines, sensors and controls). In addition to private research funds, several of the identified technologies have received some public R&D support.

There are, however, a large number of technologies that already have made some headway into the marketplace or are at the prototype testing stage, and candidates for demonstration for potential customers to gain comfort with the technology. While we recommend further demonstration and dissemination of the technology, it is often difficult to understand what is limiting their uptake without more comprehensive investigation of market issues. Some of the technologies in this category are common in European countries or Japan but have not yet penetrated the U.S. market. Others are being newly developed in the U.S. and face challenges in reducing the perceived risks by investors. Two technologies, motor system optimization and pump efficiency improvement are opportunity for training programs similar to those developed by the U.S. Department of Energy for the compressed air system management. For advanced industrial CHP turbine systems the major recommended activity is removal of policy barriers. For others, their unique markets will dictate the form of the educational and promotional activities.

Table 6. Technologies with High Energy Savings and a High Likelihood of Success

Technology	Code	Total Energy Savings	Likelihood of Success	Recommended Next Steps
Efficient cell retrofit designs	Alum-2	High	High	Demo
Advanced lighting technologies	Lighting-1	High	High	Dissem., demo
Advance ASD designs	Motorsys-1	High	High	R&D
Membrane technology wastewater	Other-3	High	High	Dissem., R&D
Sensors and controls	Other-5	High	High	R&D, demo, dissem.
Black liquor gasification	Paper-1	High	High	Demo
Near net shape casting/strip casting	Steel-2	High	High	R&D
New EAF furnace processes	Steel-3	High	High	Field test
Oxy-fuel combustion in reheat furnace	Steel-4	High	High	Field test
Advanced CHP turbine systems	Utilities-1	High	High	Policies
Autothermal reforming-ammonia	Chem-7	High	Medium	Dissemination
Membrane technology - food	Food-3	High	Medium	Dissem., R&D
Advanced lighting design	Lighting-2	High	Medium	Dissem., demo
Compressed air system management	Motorsys-3	High	Medium	Dissem.
Motor system optimization	Motorsys-5	High	Medium	Dissem., training
Pump efficiency improvement	Motorsys-6	High	Medium	Dissem., training
High efficiency/low NO_X burners	Other-2	High	Medium	Dissem., demo
Process integration (pinch analysis)	Other-4	High	Medium	Dissemination
Heat recovery - paper	Paper-5	High	Medium	Demo
Impulse drying	Paper-7	High	Medium	Demo
Smelting reduction processes	Steel-5	High	Medium	Demo
Advanced reciprocating engines	Utilities-2	High	Medium	R&D, demo
Fuel cells	Utilities-3	High	Medium	Demo
Microturbines	Utilities-4	High	Medium	R&D, demo
Inert anodes/wetted cathodes	Alum-4	High	Medium	R&D
Advanced forming	Alum-1	Medium	High	R&D
Plastics recovery	Chem-8	Medium	High	Demo
Continuous melt silicon crystal growth	Electron-1	Medium	High	R&D
100% recycled glass cullet	Glass-1	Medium	High	Demo
Anaerobic waste water treatment	Other-1	Medium	High	Dissem., demo
Dry sheet forming	Paper-4	Medium	High	R&D, demo
Biodesulfurization	Refin-1	Medium	High	R&D, demo

CONCLUSIONS AND FUTURE WORK

The study identified almost 200 emerging energy-efficient technologies in industry, of which we characterized 54 in detail. While many profiles of individual emerging technologies are available, few reports have attempted to impose a systematic approach to the evaluation of the technologies. This study provides a way to review technologies in an independent manner and to evaluate claims, as well as to provide a perspective on the potential role of technologies.

There are many interesting lessons to be learned from some further investigation of technologies identified in our preliminary screening analysis. The analyses are useful to evaluate some of the claims made by developers, as well as to evaluate market potentials for the U.S. or specific regions. The report shows that many new technologies are ready to enter the market place, or are currently under development, stressing that we are not running out of technologies to improve energy efficiency, economic and environmental performance, and neither will we in the future. The study shows that many of the technologies have important non-energy benefits, ranging from reduced environmental impact to improved productivity. Several technologies have reduced capital costs compared to the current technology used by those industries.

The current report has a number of limitations. There is still a need for further evaluation of the profiled technologies. In particular, further quantifying the other benefits based on the experience from technology users in the field could be an important direction to pursue for follow-up and ideally should be in any type of integrated technology scenario. More detailed assessment of these may help to better evaluate market opportunities. In addition, our selection of a limited set of 54 technologies was an arbitrary constraint based on limited resources. A number of the initial technologies screened appeared very interesting and warrant further study, but were eliminated due to the resource constraint. In addition, the initial list of candidate technologies should not be viewed as all-encompassing. The authors are confident that we missed many promising existing technologies, and by their nature new technologies will be continually emerging. Ideally, the effort reflected in this report should become the beginning of a continuing process that identifies of emerging technologies, profiles of the most promising and tracks the market success for those profiled. An interactive database may be a better choice. This would allow the continual updating of information, rather than providing a static snap-shot of the industrial technology universe.

While this report focuses on the U.S., state or region specific analysis of technologies may provide further insights in opportunities, specific for the region served. Regional specificity is determined by the type of users (i.e. industrial activities) in the region, as well as the available developers in a region. Combining region-specific circumstances with technology evaluations may lead to varying needs and policy choices for regional, e.g. state or utility, agencies. A regional focus would also allow the assessment of different technologies, specific for that region.

Acknowledgements. The work of LBNL was supported by Pacific Gas & Electric, the Office of Air and Radiation, U.S. Environmental Protection Agency and the Office of Industrial Technologies, U.S. Department of Energy, through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The work of ACEEE was supported by the New York State Energy Research & Development Authority, the Northwest Energy Efficiency Alliance and the Iowa Energy Center.

References

Alliance to Save Energy, American Council for an Energy-Efficient Economy, Natural Resources Defense Council, Tellus Institute, Union of Concerned Scientists, 1997. "Energy Innovations: A Prosperous Path to a Cleaner Environment," Washington, DC.

Belzer, D., Roop, J., Sands, R., Greene, D. 1995. "Energy Conservation Trends: Understanding the Factors Affecting Energy Conservation Gains and Their Implications for Policy Development,". Washington, DC: U.S. Department of Energy, Office of Policy.

Bernow, S.; Cory, K.; Dougherty, W.; Duckworth, M.; Kartha, S.; Ruth, M. 1999. "America's Global Warming Solutions" A study for the World Wildlife Fund and Energy Foundation, Boston, MA: Tellus Institute.

Bureau of Economic Analysis, U.S. Dept. of Commerce, 2000. Summary Statistics from the BEA website, http://www.bea.doc.gov/.

Decanio, S. and Laitner, J. 1997. "Modeling Technological change in Energy Demand Forecasting," *Technological Forecasting and Social Change* **55** pp.249-263.

Energy Information Administration (EIA), U.S. Department of Energy, 2000. Summary Statistics from the EIA website. www.eia.doe.gov

Energy Information Administration (EIA), U.S. Department of Energy, 1999. Annual Energy Outlook 2000. Energy Information Administration: Washington, DC.

Golove, W. H. and Schipper, L. 1996. "Long-term Trends in U.S. Manufacturing Energy Consumption and Carbon Dioxide Emissions," *Energy* **21** pp.683-692.

International Iron and Steel Institute, 2000. Statistical Data on continuous casting. http://www.worldsteel.org/trends_indicators/figures_7.html

Martin, N. Worrell, E., Sandoval, A. Bode, J., Phylipsen, D. Ed. 1999. "Industrial Energy Efficiency Policies: Understanding Success and Failure," Workshop proceedings. Berkeley, CA: Lawrence Berkeley National Laboratory.

Martin, N., Worrell, E., Price, L.K., Ruth, M.B., Anglani, N., Elliott, N., Shipley, A., Thorne, J., Nadel, S., 2000. "Emerging Energy-Efficient Industrial Technologies," Berkeley, CA/Washington, DC: LBNL/ACEEE.

Nadel, S., Rainer, L., Shepard, M., Suozzo, M., and Thorne, J., 1998. "Emerging Energy-Saving Technologies and Practices for the Buildings Sector," Washington, DC: ACEEE.

Worrell, E., Levine, M., Price, L., Martin, N., Van Den Broek, R., and Blok, K., 1997. "Potentials and Policy Implications of Energy and Material Efficiency Improvement," New York: United Nations Division for Sustainable Development, United Nations.